Modeling Water Waves with Smoothed Particle Hydrodynamics

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LONG-TERM GOALS

Smoothed Particle Hydrodynamics (SPH) is a meshless numerical method that is being developed for the study of nearshore waves and other Navy needs. The Lagrangian nature of SPH allows the modeling of wave breaking, surf zones, ship waves, and wave-structure interaction, where the free surface becomes convoluted or splash occurs. Including these phenomena in a numerical model that is robust enough for Navy use: GPUSPH.

OBJECTIVES

To improve the ability of the meshfree Lagrangian numerical method Smoothed Particle Hydrodynamics (SPH) to be a useful hydrodynamics model for breaking waves and the nearshore zone, particularly for case where spray and splash are important. To utilize the massively parallel graphics processing units on computers to develop the GPU-accelerated model GPUSPH to solve a number of problems relevant to the U.S. Navy. The science objective is to be able to accurately model the complex flows associated with breaking water waves, including instantaneous motions as well as (time-averaged) wave-induced flows, such as undertow, longshore currents, and rip currents.

APPROACH

The approach is based on improving various aspects of the SPH code, including the continued development of a multi-graphics processing unit (GPU) version of the code (GPUSPH); applying the code to more validation tests; and to examine in some detail new aspects of the model by applying it to different situations relevant to Navy needs.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**
4. TITLE AND SUBTITLE **Modeling Water Waves with Smoothed Particle Hydrodynamics**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The Johns Hopkins University,Department of Civil Engineering,3400 North Charles Street,Baltimore,MD,21218**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

- GPUSPH has been shown to model wave shoaling, wave refraction, wave diffraction and harmonic generation in shallow water.
- Radiation stresses of waves in GPUSPH are correctly modeled.
- Nearshore circulation including rip channels and return flows are correctly modeled.
- Coherent turbulent structures created by the wave breaking process are modeled with GPUSPH.
- Pressure can be stabilized within the model by using additional terms in the conservation of mass.

RESULTS

Waves in the Surf Zone

During previous years, we have shown the wave modeling capabilities of GPUSPH for surf zones. One of these tests was a comparison to the wave tank experiment of Drønen et al. (2002); see Jalali Farahani et al. (2012, 2013). This experiment was designed to show the generation of a rip current excised into an offshore sand bar, similar to Haller et al. (2002). The experiment of Drønen et al. (2002) consists of a composite beach profile with a 'sand bar' over part of the width of the tank. Waves created by a moving wave paddle propagate to the sand bar and begin breaking except where the sand bar is absent (the rip channel). Wave shoaling, breaking, refraction, and diffraction are modeled by GPUSPH as well as wave-current interation (as seen at the right side of the figure) and the nonlinear harmonic generation in the shallow water over the shoal. Harmonic generation, which is the decoupling of harmonics (that comprise the waves) in shallow water (Mei and Ünlüata, 1972) is due to the non-dispersive nature of waves in shallow water and is clearly modeled by the GPUSPH particle scheme.

In this experiment, the mean (Eulerian) currents, such as the rip currents and the nearshore circulation, were shown to match well with the laboratory measurements. To obtain Eulerian measurements with a the Lagrangian SPH method, a 3D grid of fixed measurement points was constructed with flow properties obtained by using SPH kernel averaging of particles around the mesh points. Using the results at these fixed points and integrating over the depth and over a wave period gave the mean flows. Recently we have calculated the radiation stresses under the waves and compared to both theory and experimentally-computed radiation stresses. Since the modeling of the circulation had worked well, there is no surprise that the GPUSPH modeling of radiation stresses that drive the flows also was successfully modeled by the SPH method.

Waves and Coherent Turbulent Structures Under Periodic Breaking Waves

For progressive waves, breaking plunging waves create horizontal vorticies (the tube or barrel) and splash-up. While these vortices and splash-up seemingly should be two-dimensional, the inherent instabilities in the waves have seeded an immense amount of 3-D perturbations in the roller region.

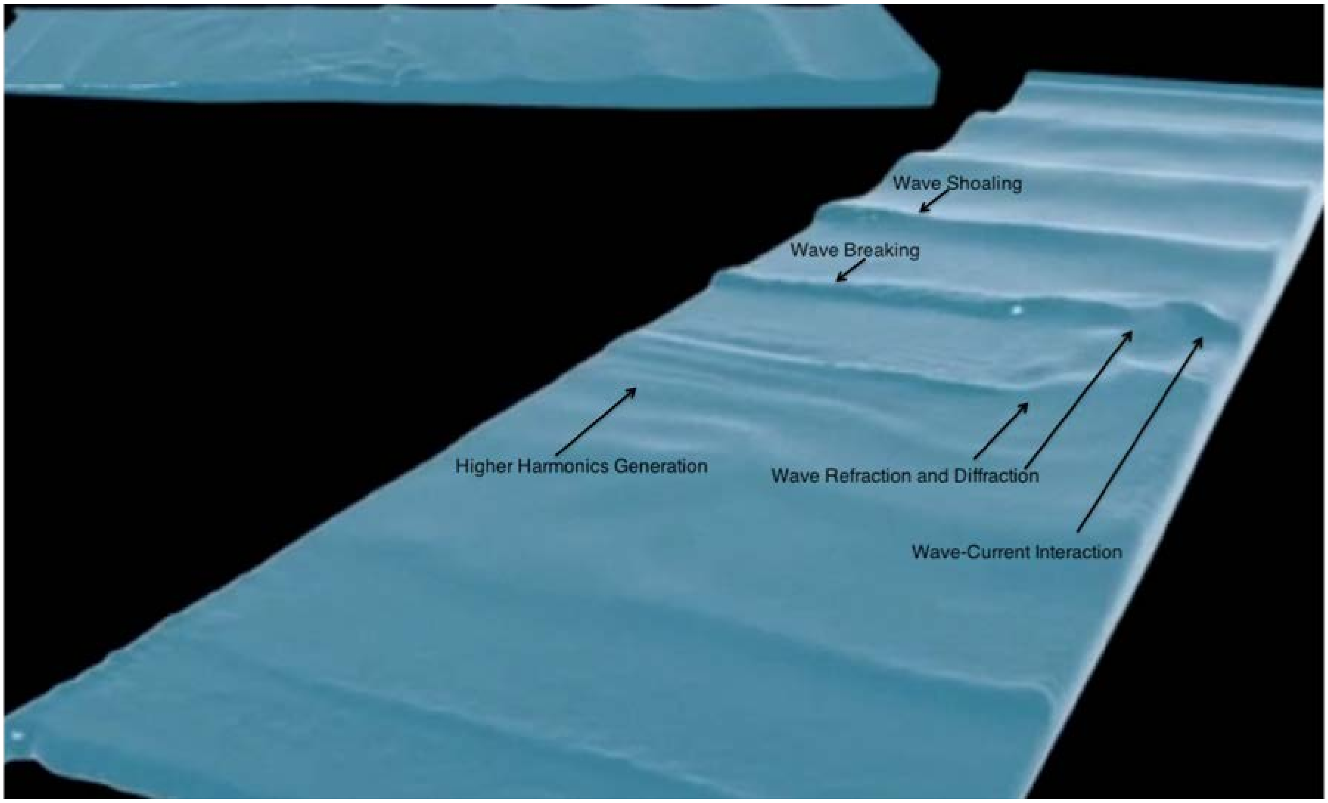

Figure 1. Numerical results of rip current simulation based on the laboratory experiments of Drønen et al. 2001. The wavemaker is located at the upper right, and an idealized sand bar on the left side. In this frame, wave breaking, harmonic generation over the bar, wave refraction, diffraction, shoaling, and wave-current interaction are all visible. Visualization provided by Templeman Automation.

Nadaoka et al. (1979) observed coherent vortical structures that were created by breaking waves and that are persistent within the surf zone. They referred to these flow structures that dragged bubbles into the water column from the breaking roller as obliquely descending eddies (ODE). The scientific question is how does the horizontal roller that develops during breaking get transformed into a vertical structure, which resembles a tornado?

Using GPUSPH we have examined in some detail the vorticity under breaking waves as identified both by the fluid vorticity but also by the lambda 2 criterion (Jeong & Hussain, 1995), which uses the symmetric and antisymmetric components of the velocity gradient tensor to identify regions of low pressure indicative of the interior of vorticies.

Figure 2 shows the eighth wave in a sequence of waves breaking on a planar beach. The breaking roller and the splash-up are visible using the lambda 2 criterion. But surprisingly there are two large reverse horseshore vortices being left behind by the propagating wave.

In Figure 3, the vorticity associated with a horseshoe vortex is shown by examining the vorticity in the onshore direction in a plane that is parallel to the wave crest. It shows that the rotation is such that the

flow is downward in the center of the loop of the horseshoe. The net result of the flow field is that the horseshore vortex moves down into the water column.

The reverse horseshore vortex behind the wave crest is the reverse of what is seen in a turbulent boundary layer at a plate in a uniform flow. The flow overlaying the boundary layer causes horseshoe vortices to be drawn out of the boundary layer into the mean flow and the vortices rise in the water column. For waves, the situation is upside-down. Moving with the speed of a breaking wave, the turbulent roller region is situated directly over a fast moving uniform flow (speed of -C, the wave celerity). This mean flow drags the horseshore vorticies from the turbulent region and down into the water column.

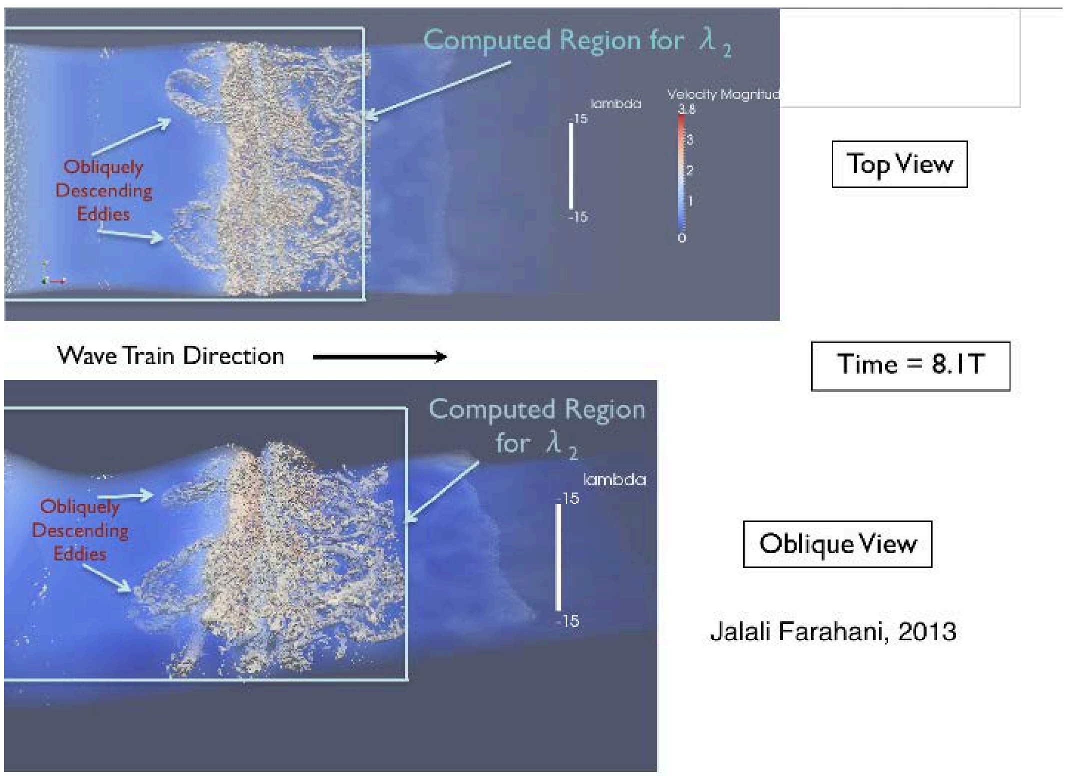

Figure 2. Coherent turbulent structures under a periodic wave in the vicinity of the wave crest. Reverse horseshoe vortices are shown at the trailing edge of the breaking wave as identified by arrows.

Turbulent Structures Under a Solitary Wave

A similar study was carried out for the coherent structures under a breaking solitary wave. Solitary waves have been used in the past as a model for either waves in the shallow water of the surf zone or as a first approximation to a tsunami. Wave data was obtain from the laboratory experiments of Ting (2006). In Figure 4, the measured water surface elevations at 12 locations down the wave tank are compared to GPUSPH with good agreement.

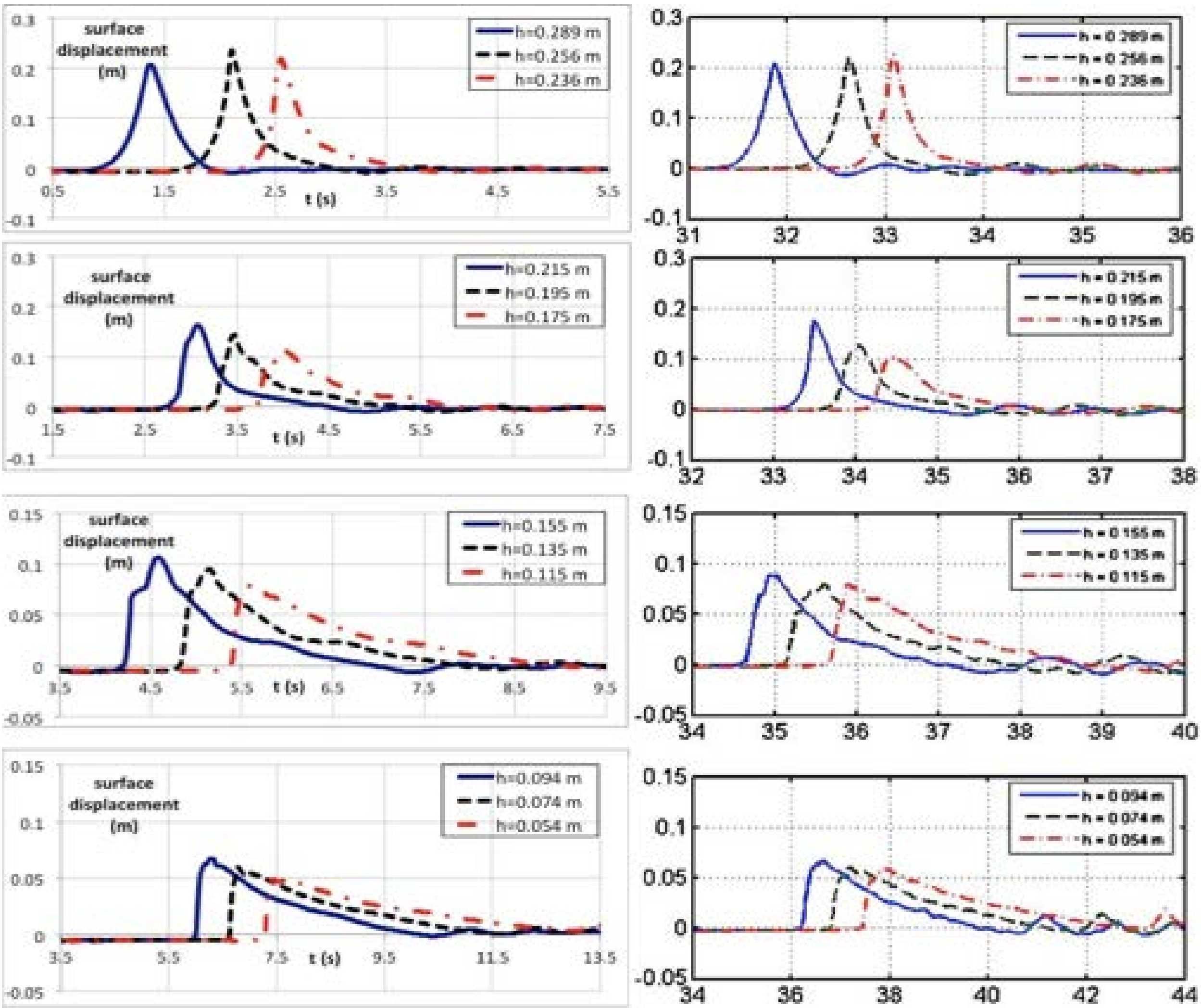

Figure 3. Comparison between GPUSPH simulated water surface elevations versus the measurements of Ting (2006) at twelve locations along the tank. The GPUSPH calculations are on the left side of the figure and the measurements are shown at the right side. There is good agreement between model and data.

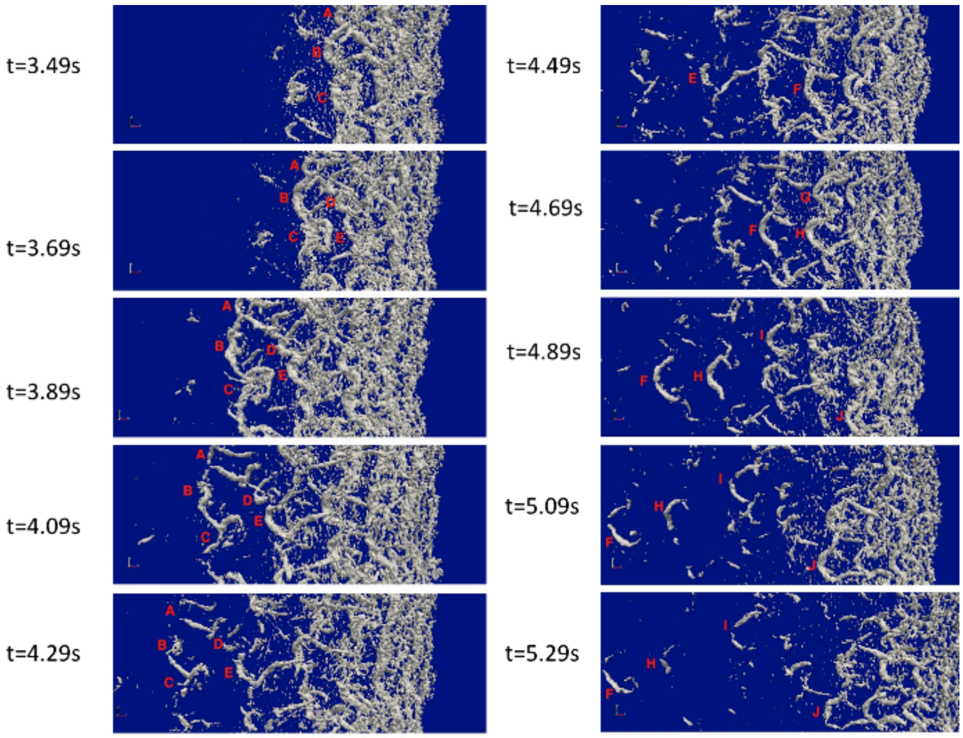

Figure 4. Horseshore vortices from GPUSPH simulation of a breaking solitary wave using lambda 2 criterion. Each frame shows a different time and vortices can be identified as time progresses by following a lettered vortex.

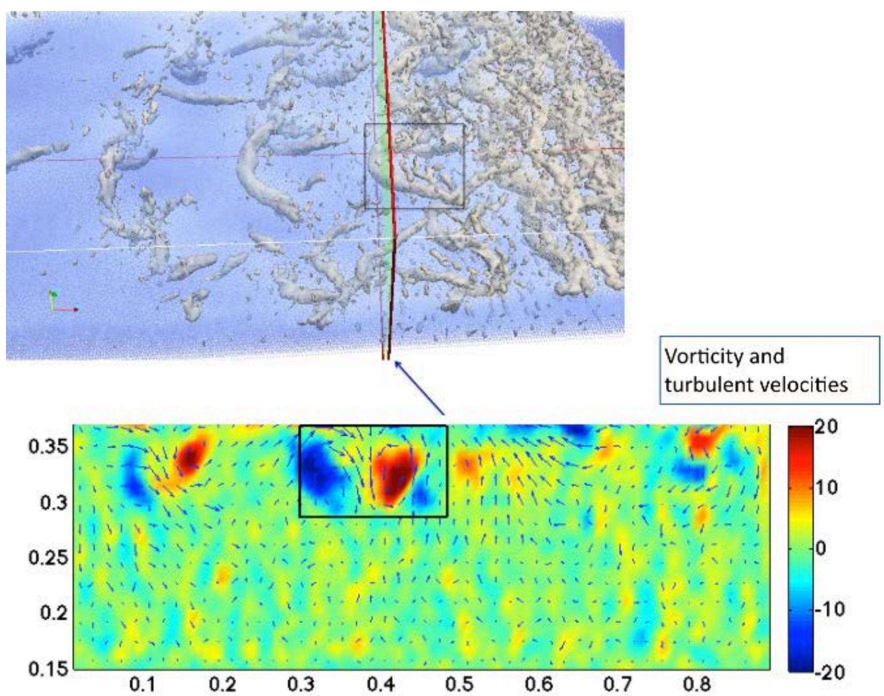

Figure 5. Coherent turbulent structures under a solitary wave in the vicinity of the wave crest. Top figure: Reverse horseshoe vortices are being left behind by the propagating wave. Bottom figure: the onshore vorticity for a plane parallel to the wave crest that intersects both legs of a horseshoe vortex

Edge Waves

Recently GPUSPH has been applied to the problem of subharmonic edge wave generation in a basin. With only normally incident waves impinging on a beach, GPUSPH is able to model the nonlinear forcing detailed by Guza & Davis (1974), which is responsible for the generation of both subharmonic and synchronous edge waves. By chosing the incident wave frequency such that integer numbers of edge waves fit within the width of the basin, resonant solutions are obtained. This topic will be explored in the second year of the project.

Floating Bodies

The open source library Open Dynamics Engine has been implemented in GPUSPH, so that floating bodies are now modeled. Collaborator Dr. Billy Edge of the North Carolina Coastal Studies Institute has modeled floating wave energy devices that respond to the forcing of the incident waves.

Improvements in GPUSPH code

Lead GPUSPH developer Alexis Hérault has developed two important improvements to the code. The first is a more efficient storage scheme for particles, such that the number of particles stored on a graphics card is doubled. In addition, homogeneous accuracy has been implemented. Since SPH is based on knowing the distance between particles, using a single origin means that calculating the distance between two neighboring particles that are far from the origin can result in a drop in accuracy as the distance is computed as the subtraction of two large vectors. The new scheme is based on using a grid of origins over the domain, such that the position of two neighboring particles is also expressed in terms of distance vectors from the local origin. This improvement greatly improves accuracy particularly for large aspect ratio problems, such as flow in long channels.

International Collaborations: We currently have a strong international collaboration in the developer group for GPUSPH with the Istituto Nazionale di Geofisica e Vulcanologia (sezione di Catania), the Università di Catania, Conservatoire National des Arts et Métiers, Paris, for the development of GPUSPH. Dr. Hérault (CNAM and INGV), Dr. Bilotta (UC), and Mr. Eugenio Rustico (BAW) are members of this collaboration. A new collaborative organization was established in 2011 that includes the original GPUSPH developers and EDF R&D (the research and development division of Electricité de France) and the German Bundes Anstalt für Wasserbau (BAW) for the joint development of GPUSPH.

A training day (Dec 10, 2013) is planned at CNAM to introduce GPUSPH to new users. The training day is in conjuction with a week-long programming marathon with the GPUSPH developers.

Ongoing efforts—There are a number major initiatives underway. The first is lead by Eugenio Rustico, which is the development of multi-CPU/multi-GPU configurations of the GPUSPH. This is critical as the GPUSPH code on a single GPU card is only capable of handling 10 million particles in a simulation. JHU has an NSF-funded 100 GPU computing cluster, which will permit extensive testing of high resolution GPUSPH simulations. Secondly, we are working on modifications to the conservation of mass equation to obtain more stable estimates of the fluid pressure. At the present

time, the Ferrari and the Molteni corrections have been programmed, with good results. More work on edge waves is underway and also work on multi-fluid GPUSPH code.

IMPACT/APPLICATIONS

Smoothed Particle Hydrodynamics is proving to be a competent modeling scheme for free surface flows in three dimensions including the complex flows of the surf zone. As the GPU hardware improves, it is expected that the resolution of SPH will increase tremendously bringing the modeling into realistically sized domains.

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